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U.S. DEPARTMENT OF ENERGY

Optimal Building Technology Selection and Operation: A Systemic Approach

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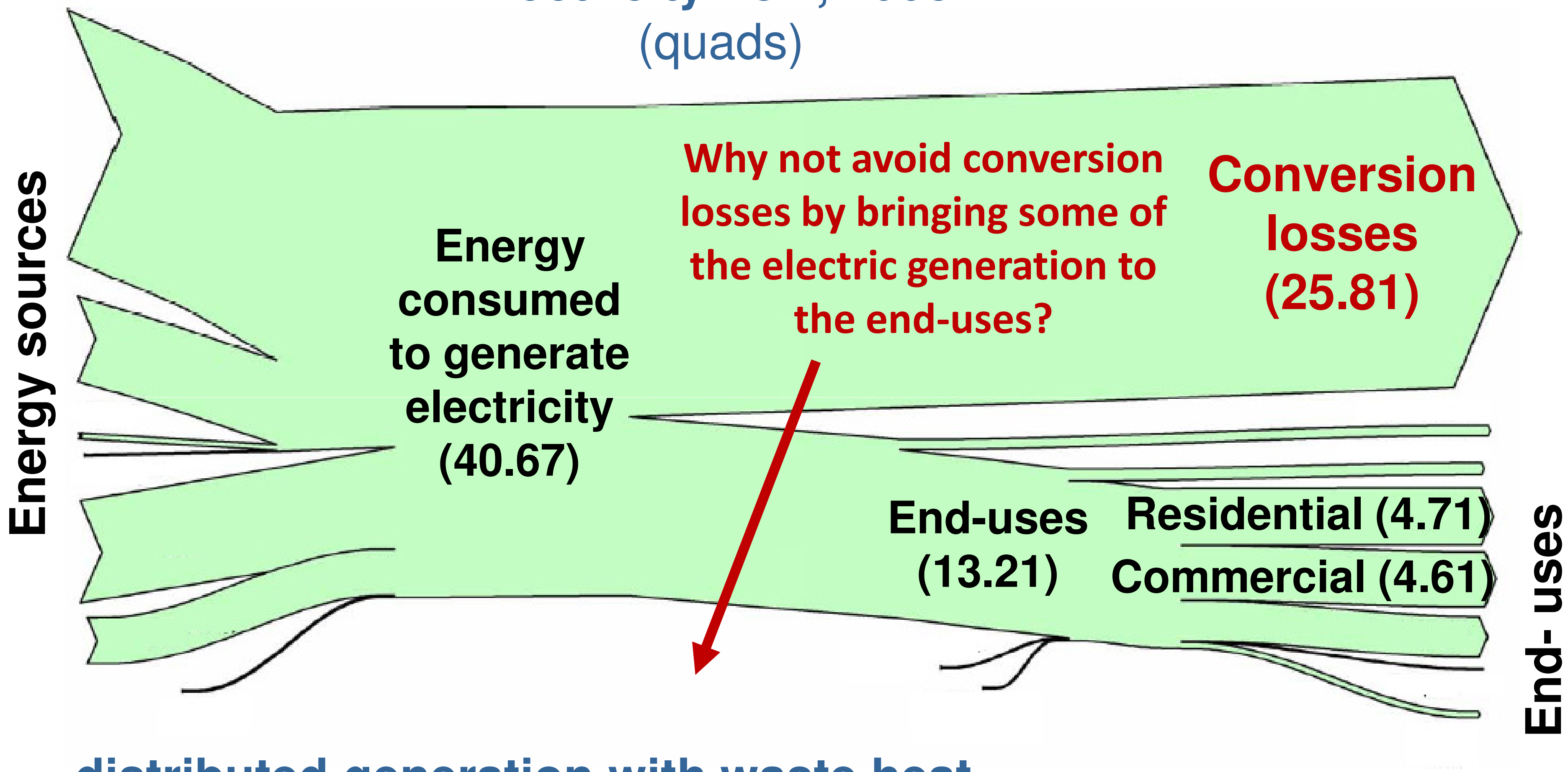
75 Years of World-Class Science 1931-2006

Outline

- Introduction: conversion losses in the electrical system
- Systemic analysis of building energy systems
  - Integrated approach, investment decisions, optimal operation of equipment
- Deterministic optimization of microgrids; the Distributed Energy Resources - Customer Adoption Model (DER-CAM),
  - Modeling
  - Example analysis on a single building; GHG abatement potential
- How to deal with uncertainty? The Stochastic Energy Deployment System (SEDS) project
- Conclusions

Introduction

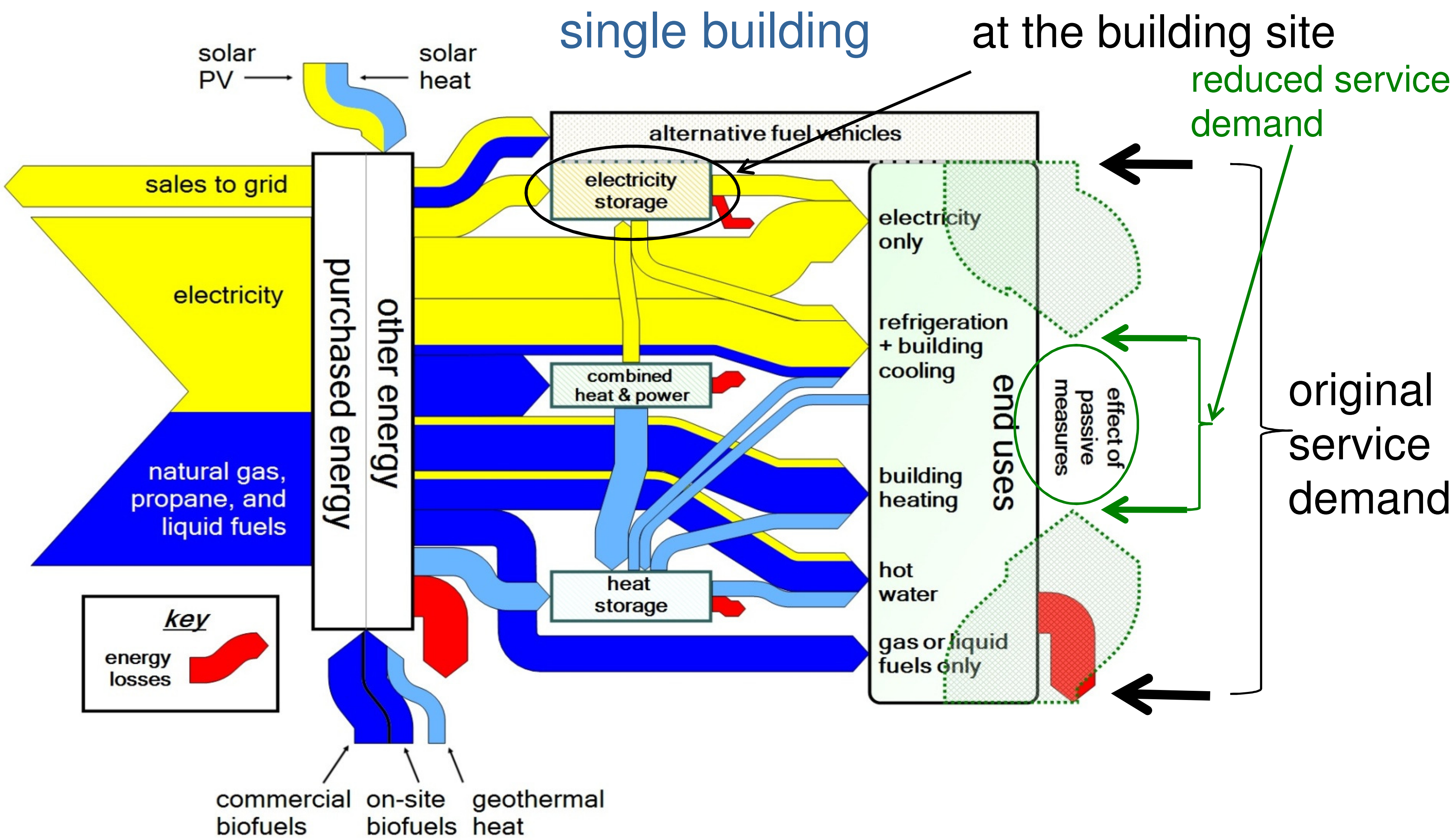
Electricity flow, 2008*
(quads)



distributed generation with waste heat utilization was the starting point 7 years ago

*source: EIA

Global concept now



The Distributed Energy Resources - Customer Adoption Model (DER-CAM)

DER-CAM model

- is a deterministic Mixed Integer Linear Program (MILP), written in the General Algebraic Modeling System (GAMS®)
- minimizes annual energy costs, CO_2 emissions, or multiple objectives of providing services on the building level (typically buildings with 250-2000 kW peak)
- produces technology neutral pure optimal results with highly variable runtime
- has been designed for more than 7 years by Berkeley Lab and academic collaborations in the US, Germany, Spain, Belgium, Japan, and Australia → exchange visitors
- might be ready for commercialization

GAMS

- is a high-level modeling system for mathematical programming and optimization
- consists of a command language and a set of integrated solvers, e.g. LP, MILP, and also NLP
- is entirely text based, easy to learn and use
- is cheap for academic users (~1 900$), but more expensive for commercial users (~11 200$) – might be a problem for DER-CAM commercialization plans

Optimization

- General optimization problem

$$\underset{\mathbf{x} \in R^n}{\text{minimize}} \quad f(\mathbf{x}) \quad \text{subject to} \quad g_i(\mathbf{x}) = 0, \; i = 1, \ldots, m.$$

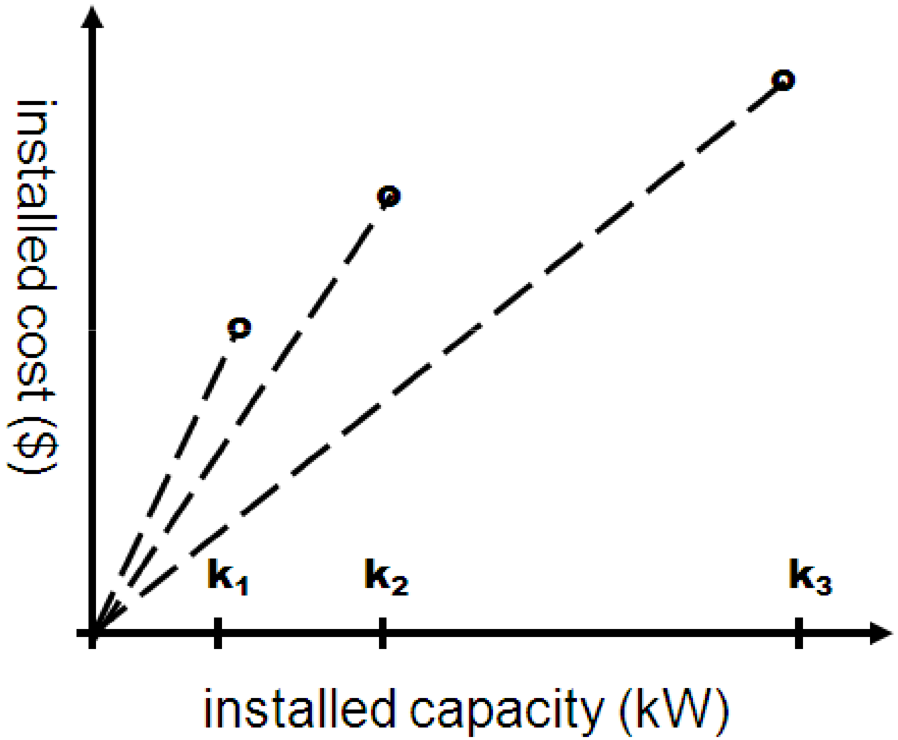
- DER-CAM is an engineering-economics optimization tool for decision support → kept stepwise linear to simplify problem and optimization

$$\text{minimize} \quad f(\mathbf{x}) = \sum_{k=1}^{n} c_k \cdot x_k \quad \text{subject to} \quad \sum_{k=1}^{n} a_{ik} \cdot x_k = 0$$

- MILP problem: some decision variables have only integer solutions, e.g. the number of installed fuel cells

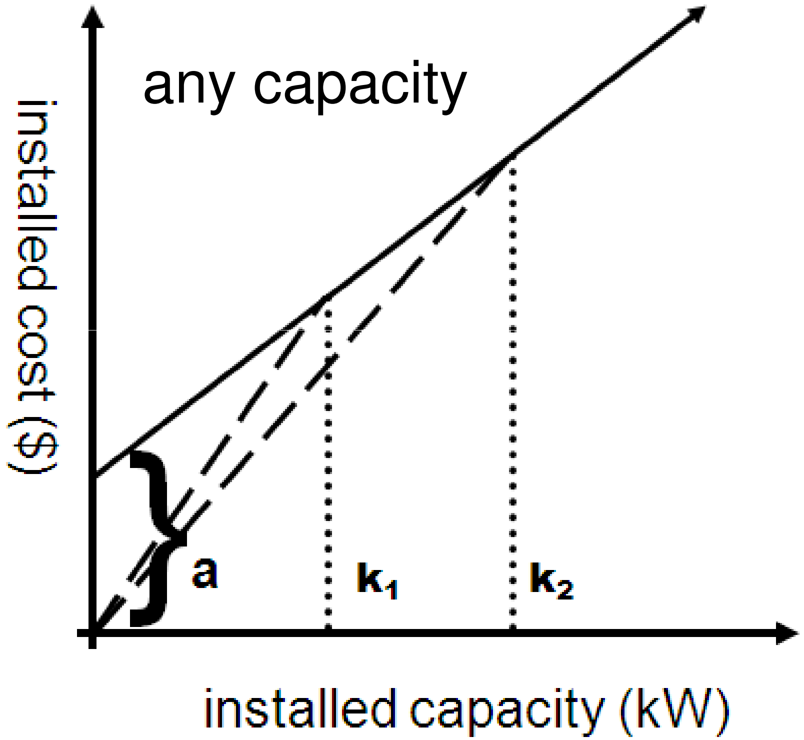
Discrete versus continuous

captures economies of scale better



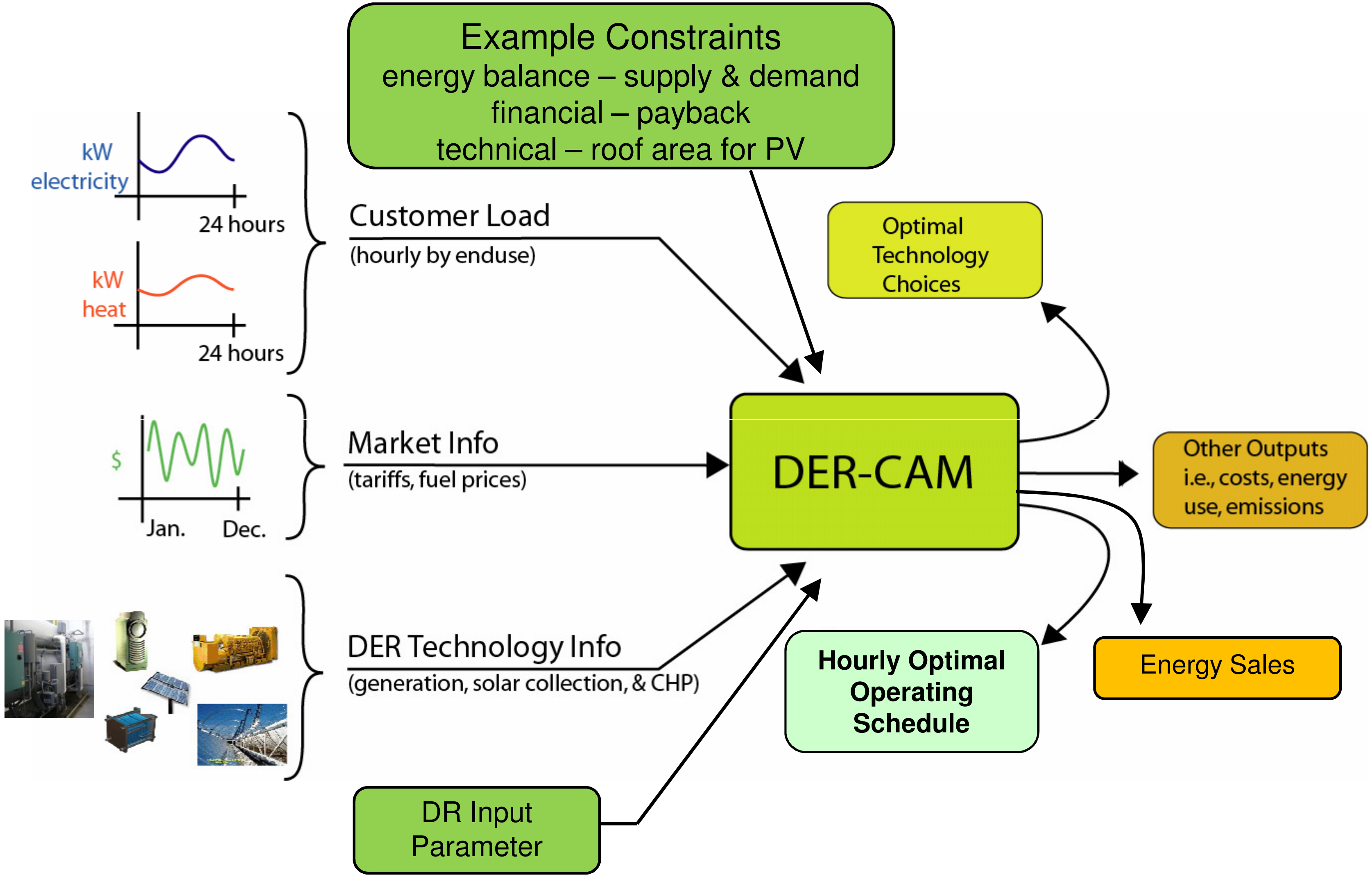
discrete technologies, e.g. fuel cells

continuous technologies improve runtime



continuous technologies, e.g. batteries

High-level schematic



Multi-criteria objective function

Multi-criteria objective function to capture different strategies of building as cost minimization, CO_2 minimization, or combinations

$$\min\left\{ w\frac{Cost}{\text{MaxCost}} + (1-w)\frac{Carbon}{\text{MaxCarbon}} \right\} \qquad 0 \le w \le 1$$

$w\ldots$ weight factor

$Cost\,(\$/a)$ and $Carbon\,(t/a)$ are objectives

$\text{MaxCost}\,(\$/\text{a})$, $\text{MaxCarbon}\,(\text{t/a})$ are parameters to make objective function dimension-less

Entire cost objective function

$$
\begin{aligned}
\min \quad Cost = & \sum_{m\in M} \mathrm{ContractDemandCharge} \cdot \max_{m\in M, t\in T, h\in H} \left\{ \mathrm{Load}_{'e',m,t,h} + \mathrm{Load}_{'c',m,t,h} \right\} + \sum_{m\in M} \mathrm{MonthlyFeeElectric} \\
& + \sum_{m\in M} \sum_{i\in I} \left(DERInvestment_i \cdot \mathrm{Maxp}_i + Capacity_{'pv'} \right) \cdot \mathrm{StandbyCharge} + \sum_{m\in M} \sum_{p\in P} \sum_{t\in T} \sum_{h\in p} ElectricityPurchase_{m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{ElectricityRate}_{m,p} \\
& + \sum_{m\in M} \sum_{d\in D} \mathrm{MonthlyDemandRates}_{m,d} \cdot \max_{t\in T, h\in d} \left\{ ElectricityPurchase_{m,t,h} \right\} + \sum_{m\in M} \sum_{t\in T} \sum_{d\in D} \mathrm{DailyDemandRates}_{m,d} \cdot \mathrm{N}_{m,t} \cdot \max_{h\in d} \left\{ ElectricityPurchase_{m,t,h} \right\} \\
& + \sum_{m\in M} \sum_{t\in T} \sum_{h\in H} ElectricityPurchase_{m,t,h} \cdot \mathrm{MktCRate} \cdot \mathrm{N}_{m,t} \cdot \mathrm{CTax} - \sum_{i\in I} \sum_{m\in M} \sum_{t\in T} \sum_{h\in H} GenX_{i,m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{PX}_{m,t,h} \\
& - SwitchPurchase \cdot \mathrm{StaticSwitchParameterValue} \cdot \mathrm{SwitchSize} - \sum_{m\in M} \sum_{t\in T} \sum_{h\in H} ElectricityPVExport_{m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{PX}_{m,t,h} \\
& + \sum_{m\in M} \sum_{t\in T} \sum_{h\in H} \sum_{i\in I_{NG}} \left(GenL_{i,m,t,h} + GenX_{i,m,t,h} \right) \cdot \frac{1}{\mathrm{E}_i} \cdot \mathrm{N}_{m,t} \cdot \begin{pmatrix} \mathrm{NGBasicPrice}_m \\ + \mathrm{NGCarbonEmissionsRate} \cdot \mathrm{CTax} \end{pmatrix} \\
& + \sum_{m\in M} \sum_{t\in T} \sum_{h\in H} NGforHeat_{m,t,h} \cdot \mathrm{N}_{m,t} \cdot \begin{pmatrix} \mathrm{NGBasicPrice}_m \\ + \mathrm{NGCarbonEmissionsRate} \cdot \mathrm{CTax} \end{pmatrix} + \sum_{m\in M} \sum_{t\in T} \sum_{h\in H} \sum_{i\notin I_{NG}} \left(GenL_{i,m,t,h} + GenX_{i,m,t,h} \right) \cdot \frac{1}{\mathrm{E}_i} \cdot \mathrm{N}_{m,t} \cdot \mathrm{OtherFuelPrice}_i \\
& + \sum_{m\in M} \sum_{t\in T} \sum_{h\in H} \sum_{k\in K} NGforNGChill_{k,m,t,h} \cdot \mathrm{N}_{m,t} \cdot \left(\mathrm{NGforABS}_m + \mathrm{NGCarbonEmissionsRate} \cdot \mathrm{CTax} \right) \\
& + \sum_{m\in M} \left(\mathrm{MonthlyFeeNGBasic} + \mathrm{MonthlyFeeNGforDG} + \mathrm{MonthlyFeeNGforABS} \right) + \sum_{i\in I} DERInvestment_i \cdot \mathrm{Maxp}_i \cdot \mathrm{CapCost}_i \cdot \mathrm{Annuity}_i \\
& + \sum_{k\in K} NGChillPurchaseQuantity_k \cdot \mathrm{Maxp}_k \cdot \mathrm{CapCost}_k \cdot \mathrm{Annuity}_k + \sum_{\ell\in L} \left(Purchase_\ell \cdot \mathrm{FixedCost}_\ell + Capacity_\ell \cdot \mathrm{VariableCost}_\ell \right) \cdot \mathrm{Annuity}_\ell \\
& + SwitchPurchase \cdot \left(\mathrm{SwitchSize} \cdot \mathrm{CostM} + \mathrm{CostB} \right) \cdot \mathrm{AnnuitySwitch} + \sum_{m\in M} \sum_{i\in I} DERInvestment_i \cdot \mathrm{Maxp}_i \cdot \frac{\mathrm{OMFix}_i}{12} \\
& + \sum_{m\in M} \sum_{\ell\in L} Capacity_\ell \cdot \mathrm{FixedMaintenance}_\ell + \sum_{m\in M} \sum_{k\in K} NGChillPurchaseQuantity_k \cdot \mathrm{Maxp}_k \cdot \frac{\mathrm{OMFix}_k}{12} \\
& + \sum_{m\in M} \left(\sum_{k\in K} \sum_{t\in T} \sum_{h\in H} NGChillAmount_{k,m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{OMVar}_k \right) + \sum_{m\in M} \left(\sum_{i\in I} \sum_{t\in T} \sum_{h\in H} \left(GenL_{i,m,t,h} + GenX_{i,m,t,h} \right) \cdot \mathrm{N}_{m,t} \cdot \mathrm{OMVar}_i \right) \\
& + \sum_{d\in D} \sum_{m\in M} \sum_{t\in T} \sum_{h\in H} Demand\,\mathrm{Re}\,sponse_{d,m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{DemandResponseVC}_d
\end{aligned}
$$

Example analyses

- Zero-Net-Energy (ZNE) Commercial Building Initiative (CBI) to make ZNE buildings marketable by 2025

- Use of energy efficient technologies and on-site (renewable) energy generation

- Our definition of the ZNEB constraint with in DER-CAM (Net Zero Source Energy)

$$\frac{Electricity\ Purchased - Electricity\ Exported}{\text{Macrogrid Efficiency}}$$

$$+ Natural\ Gas\ Consumed = 0; \quad \text{on an annual energy basis}$$

Questions

- How can zero net energy buildings (ZNEB) or zero carbon buildings (ZCB) be accomplished with available technology options?
- Can ZNEB be accomplished by photovoltaic and solar thermal only (Torcellini and Crawley), or would CHP be a wise choice?
- Do electric storage systems support PV penetration?
- What are the costs for reaching ZNEB / ZCB?

CA nursing home, cost minimization
(w = 1)

no subsidies

marginal CO_2 emission rate utility: 513 g/kWh

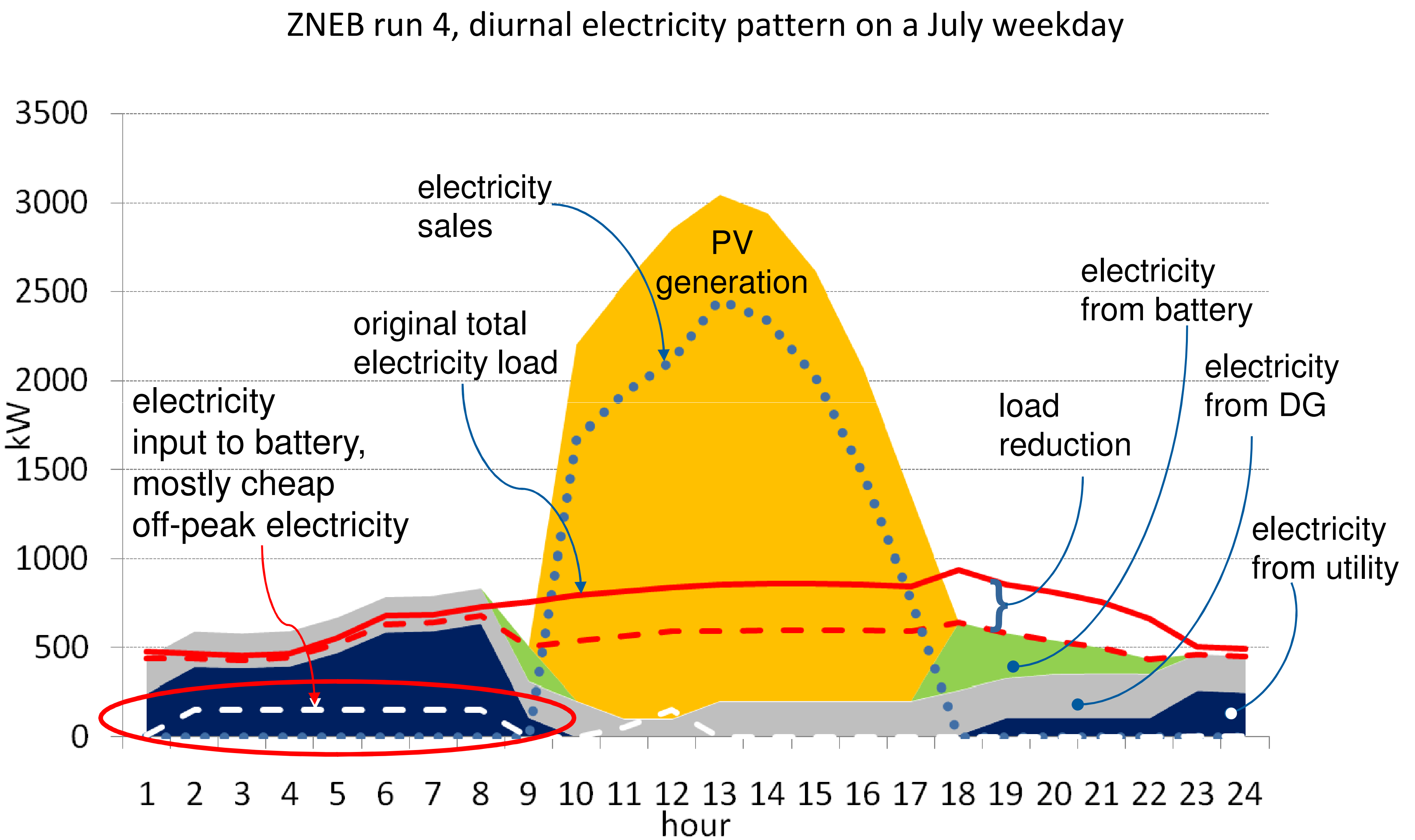
	run 1	run 2	run 3	run 4
	do-nothing	invest in all technologies	ZNEB invest in all techn..	**ZNEB low storage and low PV price**
equipment				
100 kW reciprocating engine with heat exchanger (kW)	n/a	300	0	200
abs. chiller (kW electricity displaced)	n/a	0	238	0
solar thermal collector (kW)	n/a	0	3952	0
PV (kW)	n/a	0	2408	3162
electric storage (kWh)	n/a	0	0	1514
thermal storage (kWh)	n/a	0	9897	0
annual costs (k$) and percentage savings				
total (includes annualized costs of equipment)	963.9	721.3	1782.6	829.3
savings compared to do-nothing (%)	n/a	25.2	**-84.9**	**14.0**
annual utility energy consumption (GWh)				
electricity	5.8	2.1	3.4	2.3
NG	5.7	8.9	0.004	7.5
energy sales (GWh)				
electricity	n/a	n/a	3.4	4.9
annual CO_2 emissions (t/a), *does not contain CO_2 offset due to electr. sales*				
emissions	3989	2704	1752	2548
savings compared to do-nothing (%)	n/a	32.2	**56.1**	36.1

CHP techn. plays a role

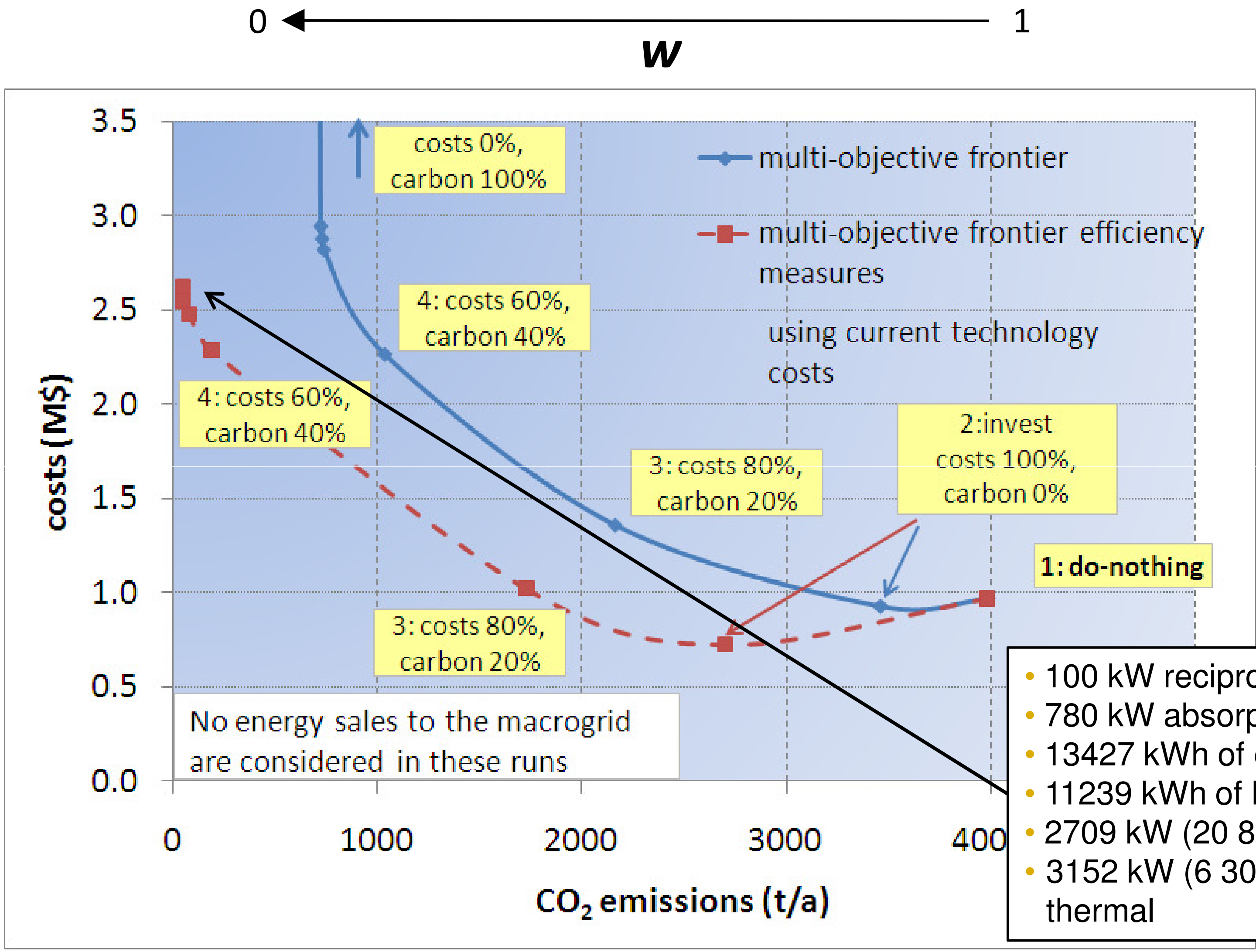
can reach ZNEB at a cost increase of approx. 85%

utilizing a *subsidy* for PV and storage of M$13→ CO_2 emission reduction cost of $259/t$CO_2$ compared to a $18/t$CO_2$ market price

CA nursing home, cost minimization (w=1)



Multi-criteria objective function
(no ZNEB)



- 100 kW reciprocating engines
- 780 kW absorption chillers
- 13427 kWh of electric storage
- 11239 kWh of heat storage
- 2709 kW (20 800 m²) of PV
- 3152 kW (6 300m²) of solar thermal

CA nursing home results

- Cost minimization: PV is not used for battery charging and both are in competition
- CO_2 minimization: PV is used for battery charging
- CO_2 minimization results in unsustainable high energy costs for the site → consideration of sophisticated efficiency measures within DER-CAM and in reality necessary
- Waste heat utilization plays a role in ZNEB

CA CHP GHG abatement

- Objective: to estimate the 2020 CO_2 abatement potential of CHP in medium-sized CA commercial buildings with electric peak loads between 100 kW and 5 MW

- Technical limitation: pick a sample of representative buildings from the California End-Use Survey (CEUS) and build a database to keep total runtime < 12 hours; automation of runs

- Use DER-CAM to examine CHP attractiveness in CA commercial buildings and its competition with technologies such as PV and solar thermal

- Estimate and report CO_2 results relative to California Air Resource Board (CARB) goal of 4MW incremental CHP in 2020 for the *entire* commercial sector

35% of commercial electric demand

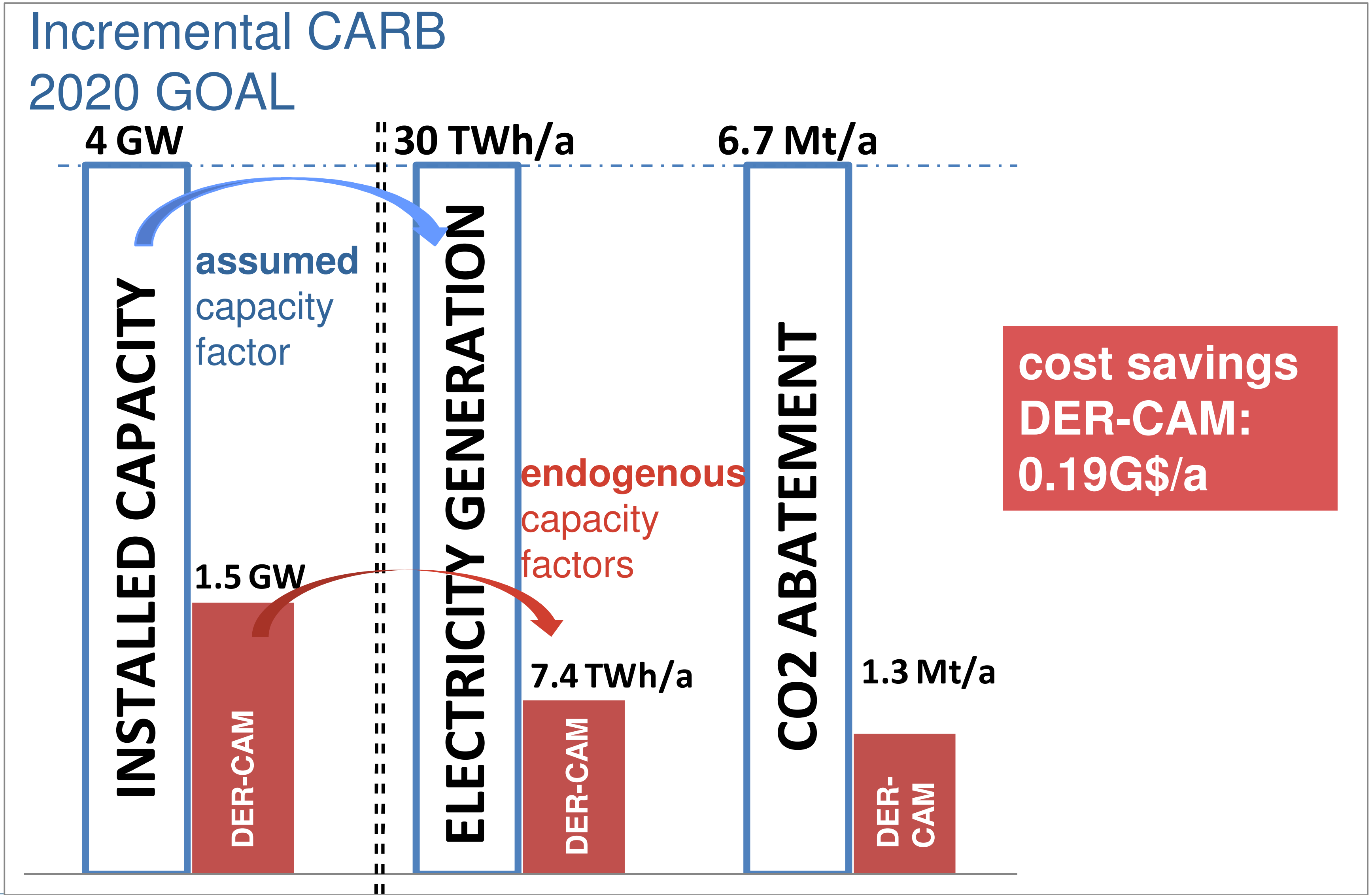
All buildings with electric peak within range of 100 kW – 5 MW

	Small Office			Large Office			Restaurant			Retail Store			Food/Liquor			Un. Warehouse		
TOTAL	1			25			1			9			9			7		
Zone	S	M	L	S	M	L	S	M	L	S	M	L	S	M	L	S	M	L
FCZ 01				☆	☆							☆			☆			
FCZ 03				☆	☆	☆						☆			☆			☆
FCZ 04			☆	☆	☆	☆			☆			☆			☆			☆
FCZ 05				☆	☆	☆						☆			☆			☆
FCZ 07				☆	☆	☆						☆			☆			
FCZ 08				☆	☆	☆						☆			☆			☆
FCZ 09				☆	☆							☆			☆			☆
FCZ 10				☆	☆	☆						☆			☆			☆
FCZ 13				☆	☆	☆						☆			☆			☆

optimizations take up to 10 hours

	School			College			Health Care			Hotel			Misc			Ref. Warehouse			
TOTAL	18			18			17			16			0			17			
Zone	S	M	L	S	M	L	S	M	L	S	M	L	S	M	L	S	M	L	TOTAL
FCZ 01		☆	☆		☆	☆		☆	☆			☆					☆		12
FCZ 03		☆	☆		☆	☆		☆	☆		☆	☆					☆	☆	16
FCZ 04		☆	☆		☆	☆		☆	☆		☆	☆					☆	☆	18
FCZ 05		☆	☆		☆	☆			☆		☆	☆					☆	☆	15
FCZ 07		☆	☆		☆	☆		☆	☆			☆					☆	☆	14
FCZ 08		☆	☆		☆	☆		☆	☆		☆	☆					☆	☆	16
FCZ 09		☆	☆		☆	☆		☆	☆		☆	☆					☆	☆	15
FCZ 10		☆	☆		☆	☆		☆	☆		☆	☆					☆	☆	16
FCZ 13		☆	☆		☆	☆		☆	☆		☆	☆					☆	☆	16
																		TOTAL	**138**

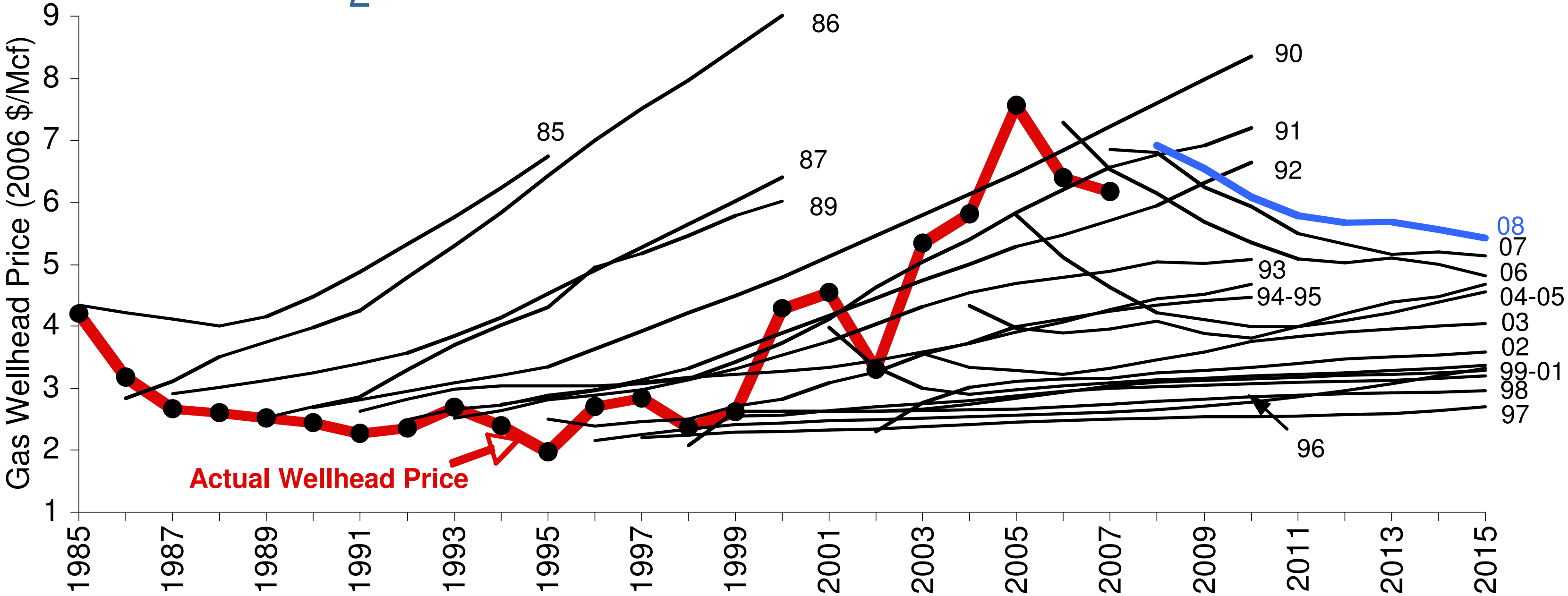
Results summary



The Stochastic Lite Building Module (SLBM) of SEDS

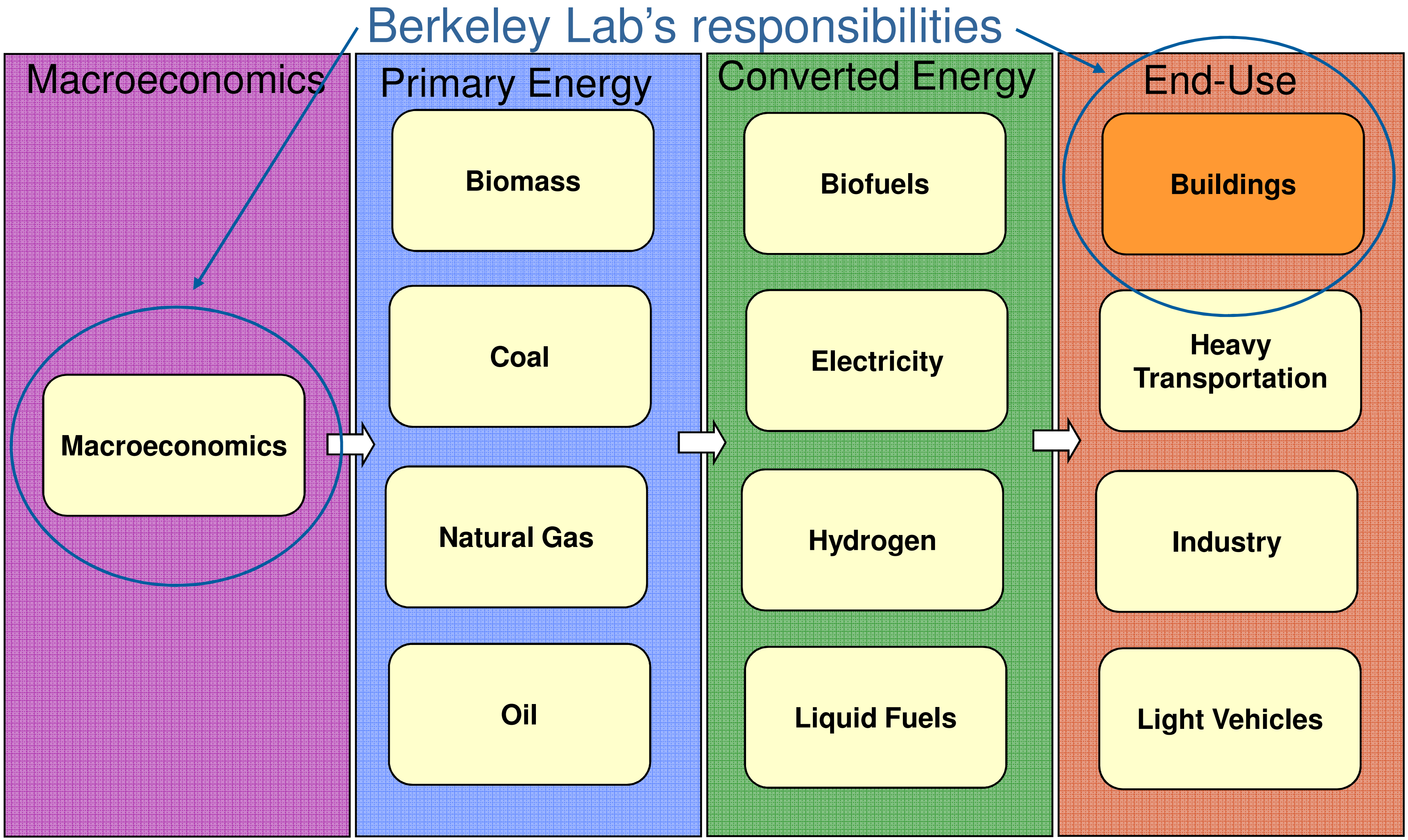
The importance of uncertainty

Government Performance Result Act of 1993 (GPRA) requires USDOE to predict and track the results of their programs→ Impact of policies and R&D on market penetration as well as CO_2 emissions needs to be estimated



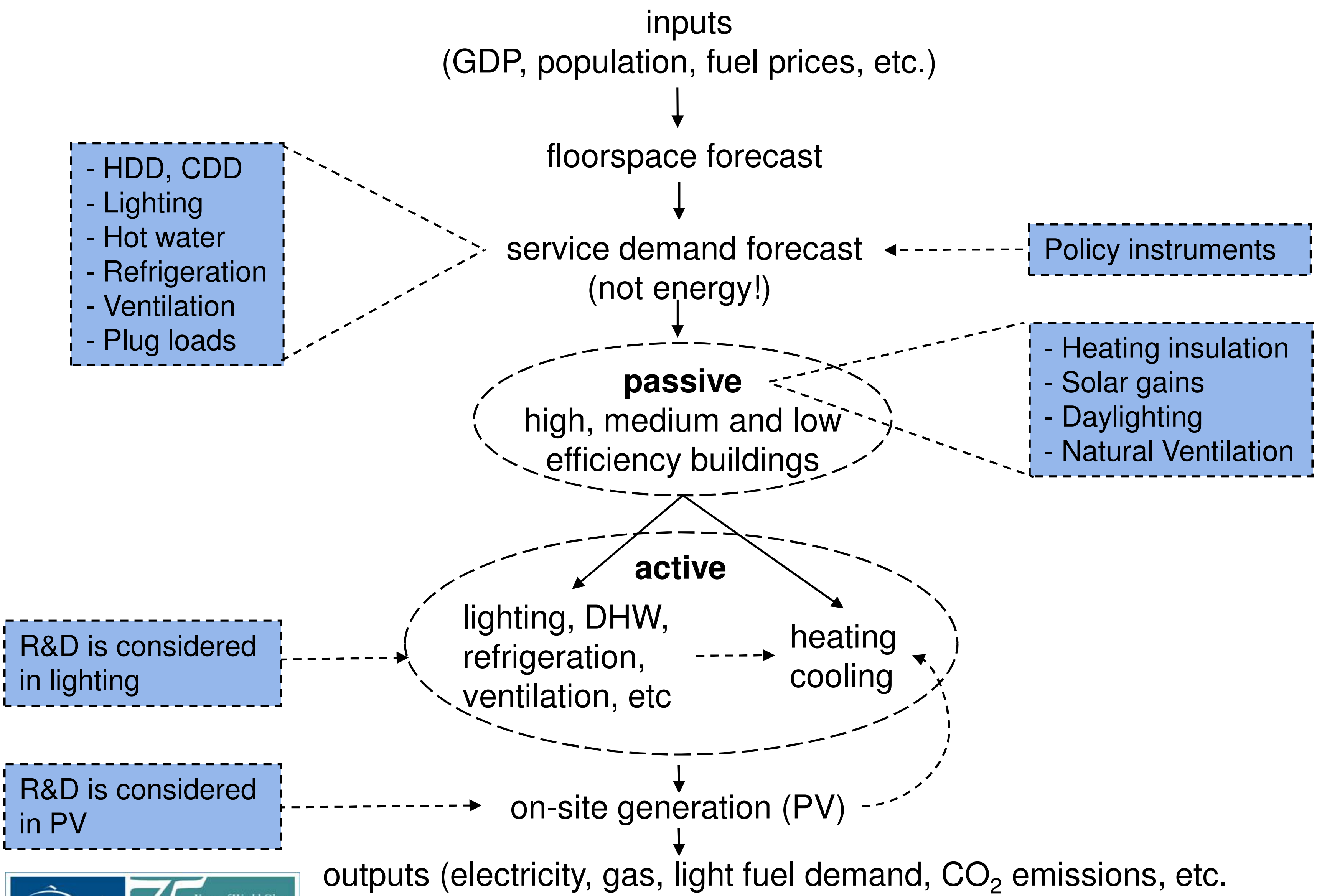
→ Point estimate forecasts are not sufficient and confidence in the estimates can beneficially be expanded to probability distributions

SEDS



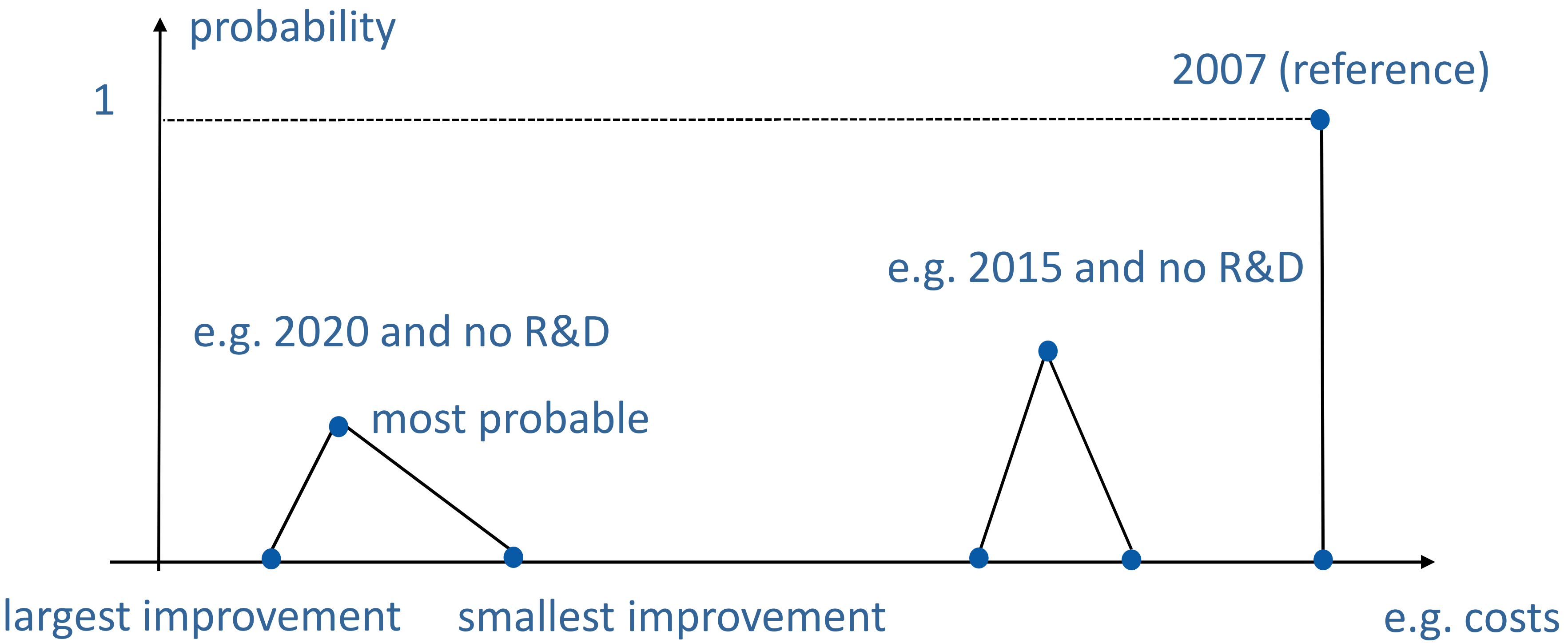
Berkeley Lab's responsibilities
Macroeconomics
Primary Energy
Converted Energy
End-Use
Macroeconomics
Biomass
Coal
Natural Gas
Oil
Biofuels
Electricity
Hydrogen
Liquid Fuels
Buildings
Heavy Transportation
Industry
Light Vehicles

SLBM logic flow



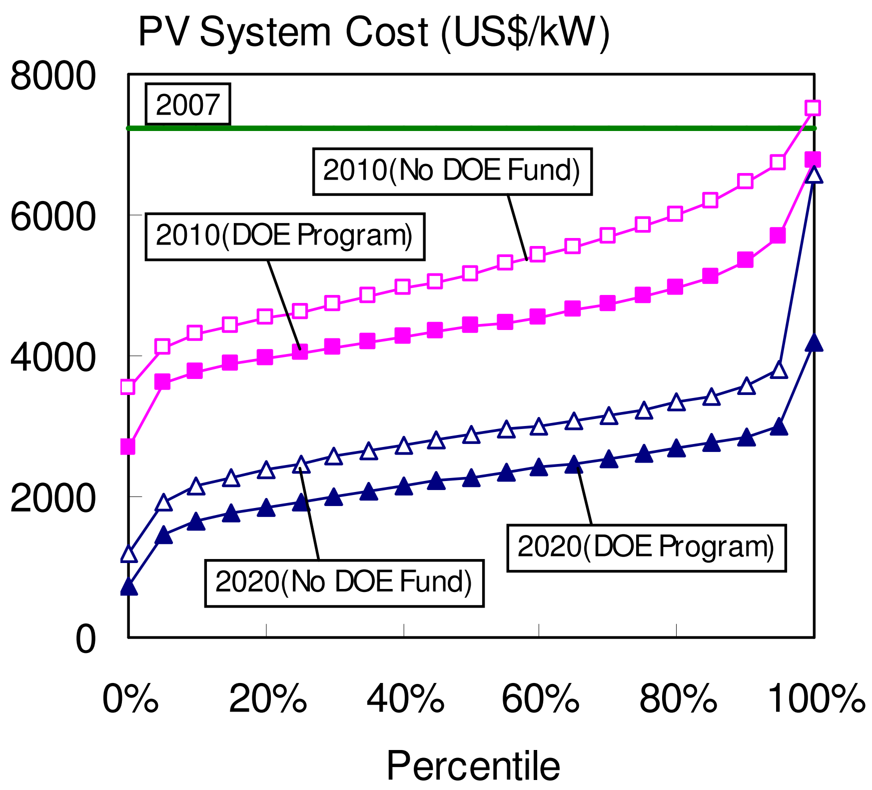
How to deal with uncertainty?

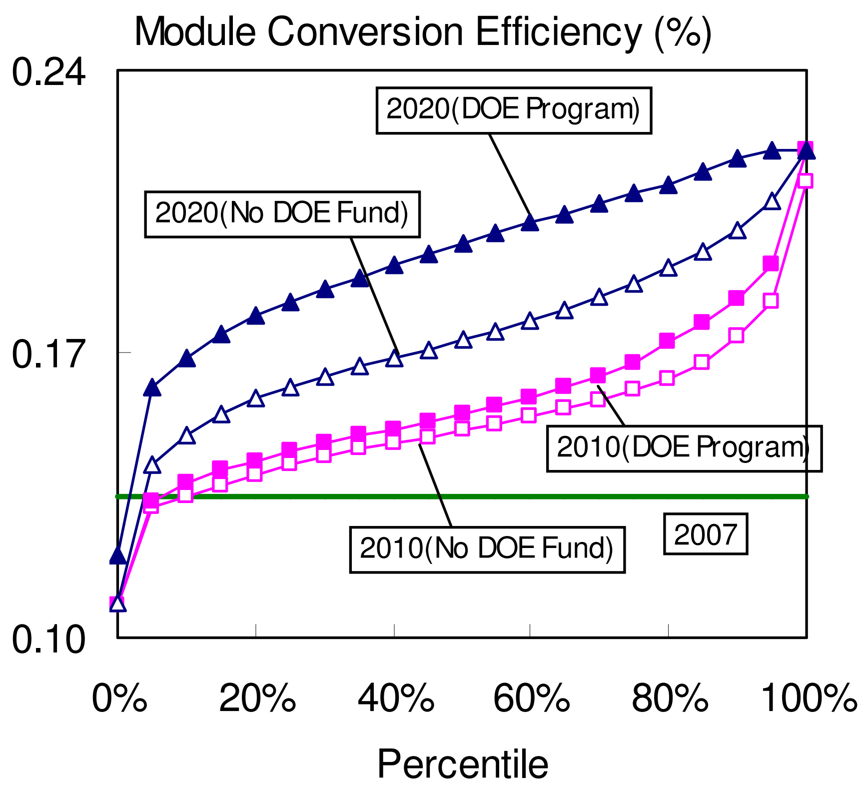
- Experts for PV, lighting and windows were asked to estimate the triangular distributions for technology parameters in 2010, 2015, and 2020
- Estimates are for different levels of USDOE R&D



Cumulative distributions

PV in commercial sector, e.g. PV system costs and efficiency

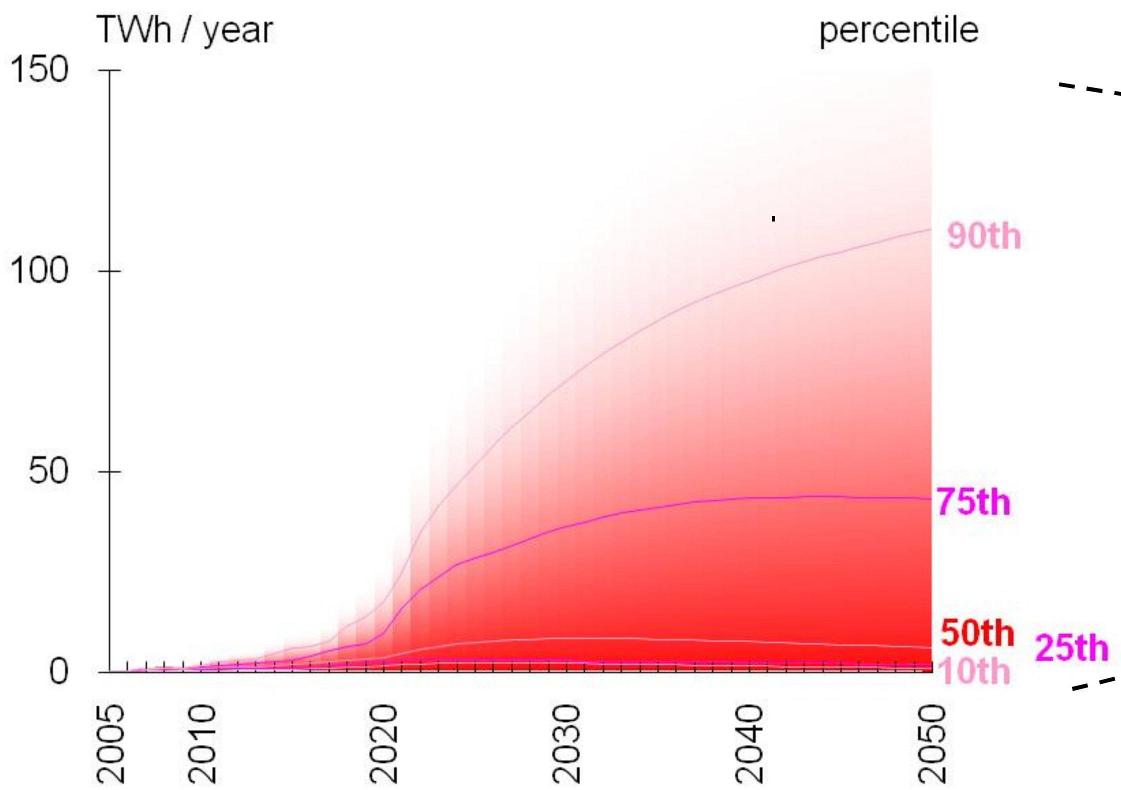


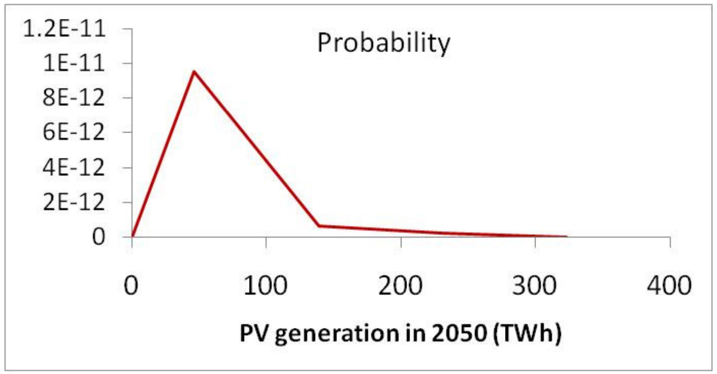


Example results

Commercial PV generation, no USDOE R&D

possible range of outcome? →probability





Conclusions

- SEDS simulations allow us to assess the risk involved in technology penetration up to 2050
- SEDS can provide us with a portfolio of technologies with different risk levels, e.g. LED is less risky in any SEDS simulation than PV
- DER-CAM can be used for policy analyses and single building optimization for a deterministic test year and delivers very detailed answers as
  - PV is mostly not used for battery charging if cost minimization is considered
  - PV is used for battery charging if CO_2 minimization is considered

Conclusions

- Waste heat utilization plays a role in ZNEB
- 1.5 GW incremental CHP capacity in medium sized CA buildings can be achieved

- Incorporation of uncertainty capabilities from SEDS to DER-CAM, stochastic optimization considering uncertainty in energy prices, tariffs, etc.

End

Thank you!

Questions and comments are very welcome.